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Evaluating the Performance, Design and Optimisation of a Solar Combisystem in the Australian Climate

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Abstract

Space heating and domestic hot water demand contributes to a significant proportion of residential energy consumption. Solar combisystems are becoming increasingly popular in servicing these energy demands through the combination of hydronic underfloor heating and domestic hot water systems.

This paper evaluates a solar combisystem design using the International Energy Agency Solar Heating and Cooling Task 26 fractional solar consumption framework, investigates design principles to improve the efficiency of the system and successfully improves the utilisation of the solar resources available.

A solar combisystem in Sydney, Australia was tested and used to validate a model in Transient System Simulation Tool (TRNSYS). This paper is intended to contribute to the existing framework and lead further developments in solar combisystem operation and design approach.

1. Introduction

The majority of the residential sector's energy requirements in Australia comes from space and water heating demand (EES DEWHA, 2008). At present, these heating demands represent a major challenge for the building industry, particularly for low-carbon buildings. With electricity prices increasing rapidly and gas prices expected to increase in the near future (Deloitte Access Economics, 2014), it is important for the residential sector to find alternative energy sources to meet their space and water heating demands. Combisystems are a promising solution to this problem.

A solar combisystem uses a single solar thermal collection system as the primary energy source to meet more than one demand in a building. In the context of this paper, a solar combisystem refers to the combination of domestic hot water (DHW) and hydronic underfloor space heating using evacuated tube collector[1]. The collector area and tank size for this system is commonly larger than a conventional solar domestic hot water system in order to meet the additional space heating demand.

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[1] The uses of 'collector' in this paper refers to a 30 tube evacuated tube collector, unless stated otherwise.

Extensive research has been conducted on solar combisystems in Europe and North America in the last 15 years. These studies range from evaluating the performance of systems in different locations to optimal sizing of system components and their control strategy (Andersen et al., 2004; Ataei et al., 2009; Hugo et al., 2010; Taousanidis and Amanatidou, 2013). The most notable of these studies has been the International Energy Agency Solar Heating and Cooling Task 26 (Weiss, 2003). Task 26 is the benchmark for design and evaluation of solar combisystems and is the most extensive research conducted on these systems to date.

A gap in current solar combisystem research is the evaluation of performance, design and optimization specific to Australia. There is a lack of monitored systems operating in Australia, leaving the efficiency and performance of these designs largely unknown. The available literature cannot be directly applied in the Australian climate due to mild temperatures resulting in different hydronic space heating requirements to those in Europe.

This paper looks at the performance of an operational system and design improvements to achieve greater auxiliary energy savings.

2. Methods

The evaluated solar combisystem configuration is shown in Figure 1. The system was an installed test site in Sydney, Australia – which consisted of evacuated tube collectors, a large storage tank of 680L, an auxiliary heat source in the form of a gas booster and a hydronic heating loop to deliver space heating to a building. This test site was used to develop a TRNSYS model which was, in turn, used to evaluate the performance of the solar combisystem across different Australian locations, optimise system design and compare performance to existing evaluated systems, such as those in IEA Task 26.

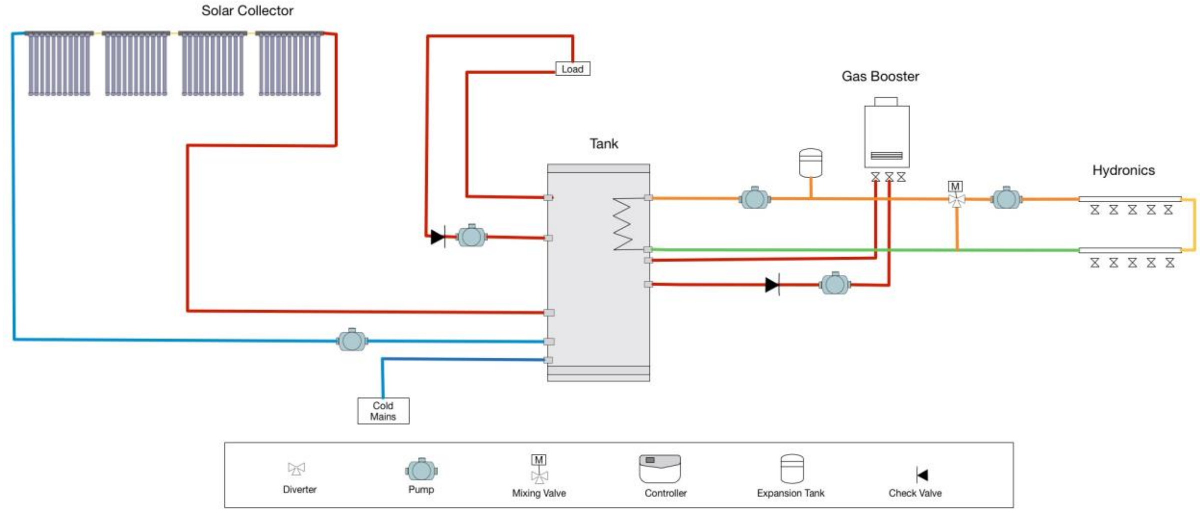

Figure 1. Modelled and evaluated solar combisystem layout

Table 1 details the components of the installed solar combisystem configuration and the physical properties of these components that were used as parameters in the TRNSYS model.

Table 1. Components of the Test Site

Component	**Type**	**Note**
Tank	680L Stainless steel	12m coil
Solar Collector	AP-30 Evacuated Tube Collector	4 collectors in series
Solar Pump	Grundfos UPS20-60N-150	Variable flowrate
Auxiliary Pump	Grundfos UPS20-60N-150	Flowrate 445 L/hr
Ring main Pump	Grundfos UPS20-60N-150	Not monitored
Hydronics Pump	Grundfos UPS20-60N-150	Variable flowrate
Gas Booster	Bosch 32L	$\eta = 83\%$
Hydronics	Auspex Radiant	2 manifolds; 7 circuits and 8 circuits
Solar Controller	DeltaSol MX Controller	Data logging capabilities
Data Logger	RESOL DL-3	Required for irradiation sensor and data logging
Irradiation sensor	RESOL CS-I	Number of sensors: 1
Temperature sensors	PT1000 Sensors	Number of sensors: 16
Flow Sensors	VFS 1-12L/min	Number of sensors: 2
	VFD 1-12L/min	Number of sensors: 1
	VFD 2-40L/min	Number of sensors: 1

2.1. Development of TRNSYS model

TRNSYS is a transient system simulation tool used to optimise and test a system over several parameter changes. It is a modular program with each module representing a particular component or group of components (A.Klein et al., 2010). A TRNSYS model allows the user to compare the performance of very different systems. In order to take advantage of this, a simulation and a methodology has to be created along with reference conditions.

The TRNSYS model was developed to simulate the test site's combined domestic hot water and hydronic space heating system. The model was validated through comparison and close correlation of results from both the model and the physical system. Error measurements were taken into account and included in the analysis of the system. The validated model was then used to create a performance curve of the solar combisystem where the global characterisation and evaluation of the system's efficiency could be determined. This was achieved by creating 36 replications of the model varying location, building heat load, and collector size, as shown in Table 2. The results from these simulations were used to determine characteristic performance curves of the solar combisystem.

Table 2 System locations, collector area and load size

Locations and latitudes	**Collector size (m^2)**	**Building heat load size (W/K)**
Sydney -33.8˚,	9.6	150
Canberra -35.3˚,	14.4	280
Melbourne -37.8˚,	19.2	500

and Hobart -42.9˚		

2.1.1. *Reference conditions*

To carry out a standard comparison between simulated systems, the reference conditions must be held constant across the initial system and the optimised system. The reference conditions involve energy loads, energy source, common parameter settings and standard components and are discussed in Table 3.

Four locations were chosen to cover the geographical range of climates in Australia where the solar combisystem market exists[2]. Hourly weather data for these locations was defined by TRNSYS TMY2 data; the input of weather data simulated the solar combisystems performance at these locations using irradiation and ambient temperature data. The inlet water temperature was chosen at 18˚C based on average Sydney water temperatures. While this will vary throughout the year and across the locations it was assumed constant. Further studies should be carried out to determine any significant effects.

Table 3 Reference conditions used across the TRNSYS simulations

Reference Condition	**Parameter**	**Assumptions**
Building heat load	UAΔT calculation. Heat loss; where U is thermal transmittance, A is area and ΔT is the indoor/outdoor temperature difference	Heating calculations use simple worst-case scenario assumptions: No solar or internal gains, and no heat storage. (American Society of Heating, 2009)
Building temperature control	22˚C and 24˚C during heating	The room temperature was set from the installed systems operating thermostat.
DHW	Family home usage pattern Temperature from city of Sydney typical mains temperature	Load profile taken from ASHRAE (2007) The temperature of the mains was not changed with location
Auxiliary Heating	Gas booster with efficiency 83%	Taken from the installed gas booster rated efficiency
Solar collector	30 tube collector, altered for 4, 6, 8 collectors	Characteristics from Apricus Australia collector

2.2. Evaluation Methods

To evaluate the performance of these systems, we employ the framework of Task 26 which developed a dimensionless indicator, the fractional solar consumption (FSC). FSC can be considered as the maximum theoretical savings a solar combisystem could reach if it had no losses. The calculation of a combisystems FSC is shown in equation (1)

$$FSC = \frac{Q_{solar,usable}}{E_{Ref}} \qquad \textbf{(1)}$$

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[2] Based on space heating demand (EES DEWHA, 2008) and an internal survey conducted at Apricus Australia

The FSC is calculated using the usable solar and reference consumption of a system (Weiss, 2003). Usable solar, is calculated summing the monthy minimum of the monthly reference consumption (kWh) or monthly global irradiation in the collector plane H (kWh/m^2) by the collector area A (m^2), as shown in equation (2). Usable solar is therefore the energy consumption of the building that could be saved by solar energy, the minimum function ensures excess consumption or irradiation is not incorporated.

$$Q_{Usable,solar} = \sum_{1}^{12} \min\left(E_{refmon}, A \times H\right) \tag{2}$$

E_{ref} is the energy consumed by a reference system. In this case, the reference system represents the sum of the space heating load, the DHW load and the losses from the tank without any solar and entirely met by the auxiliary heating. The reference consumption considers the efficiency of the auxiliary heating η_{aux}, as shown in equation (3).

$$E_{ref,month} = \frac{Q_{SH} + Q_{DHW} + Q_{loss,tank}}{\eta_{aux}} \tag{3}$$

The target function for optimisation is based on fractional thermal energy savings $f_{th,sav}$ of the solar combisystem compared to a reference system. This is related to the purchased auxiliary energy.

$$f_{\text{th,sav}} = 1 - \frac{E_{aux}}{E_{Ref}} \tag{4}$$

Fractional thermal savings is one minus the need for auxiliary energy over the total load, taking into account the efficiency of the auxiliary energy source. The closer the fractional thermal savings is to the FSC the better the solar combisystem converts all usable solar energy into real auxiliary savings.

Task 26 has shown that plotting FSC against real fractional thermal savings reveals a systems performance of converting theoretical savings to actual savings over a range of scenarios. This relationship produces a system characteristic ($f_{\text{th,sav}} = f(FSC)$) curve equation(5), allowing easily visualisation of the global behaviour of a solar combisystem and making it possible to compare different systems directly (Letz et al., 2009).

$$f_{\text{th,sav}} = a \cdot FSC^2 + b \cdot FSC + c \tag{5}$$

As the FSC is a simplified method, it is important to be aware of the main assumptions, detailed in Letz et al.(2009) .

3. Results and Discussion

The results and discussion are presented in three parts. Firstly, the performance of the installed solar combisystem is characterised. The characterisation of the solar combisystem revealed inefficiencies and provides a baseline of performance to optimise the operation of the solar combisystem. Secondly, the results from the optimisation parametric analysis are discussed, and the results implemented into a new solar combisystem design. Lastly, the optimised solar combisystem is evaluated for its performance and compared to the original design.

3.1. Performance of an installed solar combisystem design

Figure 2 includes the final performance curve of the installed system. It is the characterisation of a solar combisystem operating in Australia using the FSC-method developed and validated by Task 26 as discussed in Section 2.2, in an ideal system with no losses the FSC will be equal to the fractional thermal savings in all scenarios. Figure 2 includes: 3 reference buildings, 4 locations and varying collector sizes, the repeating markers represent the varying collector sizes for the same location and heat load. The use of this performance curve is to a) compare solar combisystem designs and allow their optimisation, b) provide a visual of the system's global behaviour, and c) evaluate the performance with varying loads. Using the curve, the following conclusions can be made about the systems performance:

- Lower FSC (Fractional Solar Consumption) are attributed to high heating loads with low solar exposure, where the tank is continuously refilled. The high turnover of energy in the tank means that the system is not saturated with auxiliary, and therefore solar can deliver a high contribution. This can be seen in Figure 2 where the FSC and Fractional Thermal Savings are within < 3% of each other. In contrast, in high FSC scenarios, auxiliary energy is used to maintain high temperatures but is not used, therefore there is limited potential for solar to contribute, and the fractional thermal savings drops. In Figure 2, the fractional thermal savings in the test site is up to 40% lower than the FSC, showing scope for optimisation

- The fact that the curve in Figure 2 is not a straight line and there is a difference between FSC and fractional thermal savings at all scenarios shows there is scope for optimisation. The study does not include inherent losses from pipes and aux start up, and hence the optimised system does not reach the maximum fractional thermal savings. Despite this, there is still scope for improvement using the same installation costs as the initial design, and more improvement may be possible with more optimisations.

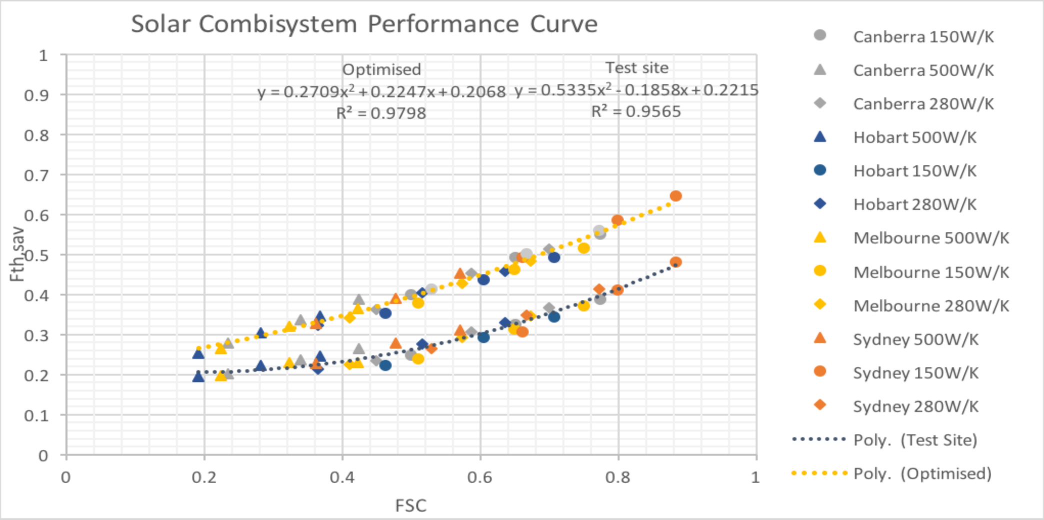

Figure 2. Solar combisystem performance curve of optimised and installed system using the Task 26 Framework

3.2. Optimisation

The TRNSYS model was further used to investigate system optimisation and to determine certain design aspects that could be used to improve the efficiency of the system. Optimisation focused on minimising the auxiliary energy input into the system and consequently increasing the utilisation of solar energy collected. Design improvements were simulated across varying locations, building heat loads and collector sizes and used to create a performance curve. This allowed the system design not only to be compared to the original performance curve but also to the solar combisystem designs evaluated by Task 26.

To optimise the solar combisystem design, a parametric analysis on the effect of reducing the tank's set point temperature that activates the auxiliary heating input was explored as well as the volume of the tank to be maintained at this set temperature by the auxiliary energy. The thermostat setting was lowered with consideration to the limitations that both DHW and hydronic heating loads must be met and the temperature must still provide thermal comfort to the occupant and the temperature must meet the Australian standards. The Australian Standards to be adhered to in this design process included; ASNZ2712 *Solar and heat pump water heaters – design and construction*, AS/NZ3498 *Authorization Requirements for plumbing products – Water heaters and hot water storage tanks*, and AS/NZ4552 *Gas fired heaters for hot water and/or centralised heating.* The relevance related to design and construction as well as several standards to comply with in design and operation covering; legionella control, tank performance standards, gas heating, simulation guidelines, and calculation guidelines. Legionella standards limited control strategies to achieve greater efficiencies.

The results of the parametric analysis simulated in TRNSYS is shown in Table 4. It can be observed that fractional thermal savings decreases with an increasing store set temperature. By lowering the set thermostat temperature of the heat store before the auxiliary booster is turned on, greater fractional thermal savings can be achieved. This is because there is less heat demand from the tank and a greater opportunity for solar contribution.

Using the results from the analysis, an alternate system configuration and logic was designed.

Table 4 Annual Auxiliary energy (MJ) needed with an increasing tank set temperature and increasing volume of tank used to store auxiliary energy, based on Sydney 500W/K with 6 collectors

		Temperature (˚C)			
		45˚C	**55˚C**	**65˚C**	**75˚C**
Storage Volume	**20%**	16350	17929	19216	22899
	30%	17169	17924	19754	23197
	40%	17168	17929	19807	23502
	50%	16830	17752	19839	23831

Table 5 Optimised system parameters

Parameter	**Optimised**	**Original**
Set temperature	45 ˚C	65˚C
Volume of tank maintained at set temperature	50%	50%
Gas booster configuration	In line with DHW, also can feed into the tank	All auxiliary energy entered the tank.

The major change in this system design was removing the auxiliary energy used to maintain DHW from the tank. The new system design will instantaneously boost the water if it is below the recommended set temperature. The auxiliary can also feed into the tank to maintain the temperature for the hydronic space heating, however this is a lower temperature allowing for a lower set temperature in the tank and reducing auxiliary energy use.

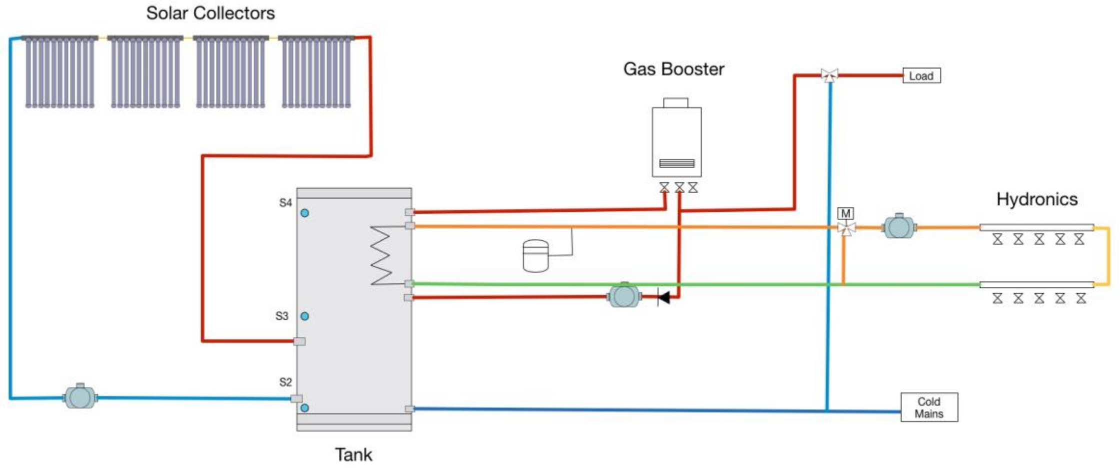

Figure 3. Schematic of optimised system design

3.3. Performance of the optimised system

Overall, the optimised system across all locations and building types generates higher fractional thermal savings demonstrating lower auxiliary energy needs. It was found that by removing the need for the auxiliary energy to directly enter the tank and to boost DHW in before delivery to the load that fractional thermal savings could be increased by up to 15%, shown in Figure 2.

Presenting the actual thermal savings of the optimised system against the original thermal savings in Figure 4 shows Sydney may have the highest fractional thermal savings but when put into annual thermal savings it produces the least amount of actual energy savings. A solar combisystem will provide the greatest savings in climates similar to that of Canberra. The highest annual thermal savings are achieved in climates such as Canberra, translating to the highest monetary savings. This is due to high solar resource and a cool temperate climate.

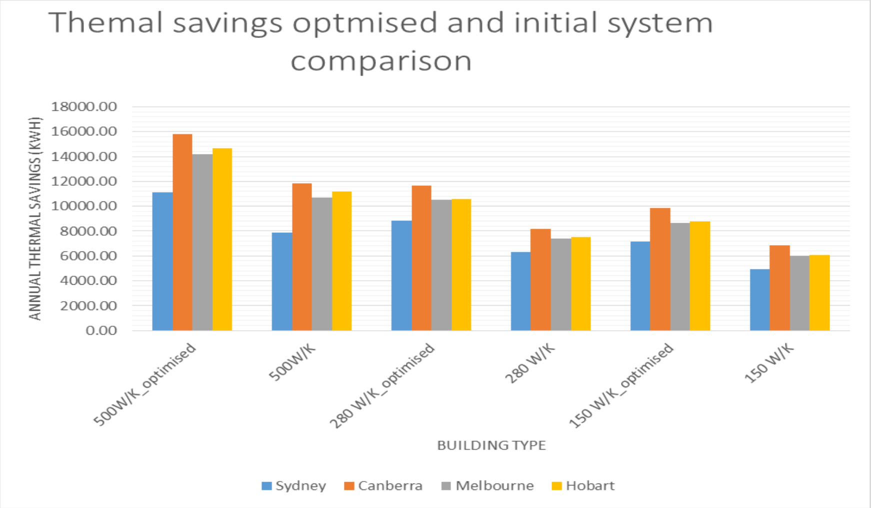

Figure 4 Thermal savings of original and optimised system designs

Figure 2 is the final performance curve for the optimised solar combisystem plotted alongside the original performance curve. The new optimised curve sits above the original indicating a more efficient system design. For every point of FSC, the optimised system has a greater fractional thermal savings. The design changes were successful and a greater solar contribution was obtained for every FSC value. The optimised curve has a more consistent performance across different loads as the solar contribution is less reliant on the system's 'saturation'. This indicates a better system design and success of an efficient auxiliary design.

The curves generated in this paper were compared to those systems evaluated in Task 26 in Figure 5, linking the paper back to the literature. A few system designs were chosen from the Task; systems #3a[3], #8[4] and #15[5]. The worst performing solar combisystem is that of the initial solar combisystem design evaluated in this paper. The optimised lies in-between System #15 and #3a. There are limitations associated with the comparison, Task 26 used flat plat collectors and this study used evacuated tube collectors which have different efficiencies and therefore affecting the performance curve. The optimised system design from this study follows similar trends to some of the high preforming combisystems from Task 26, illustrating the successful optimisation of the original system.

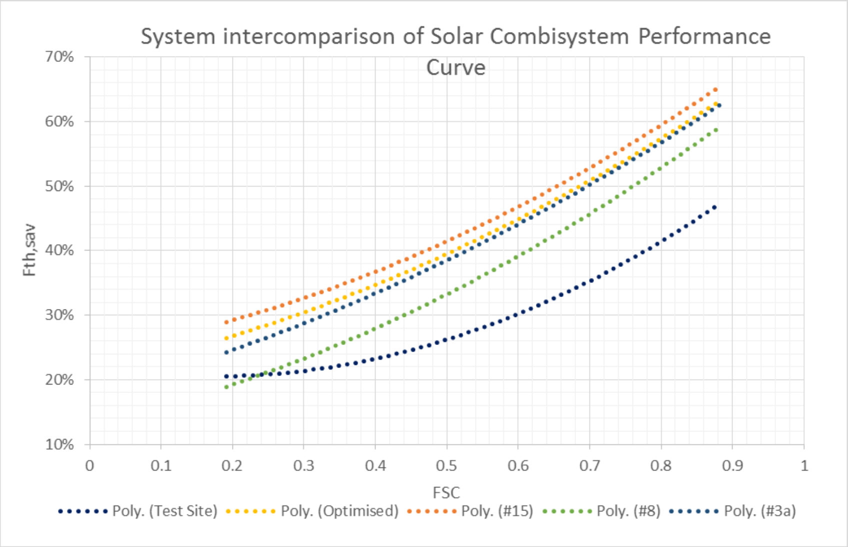

Figure 5 Compariason of Test Site and Optimised system to solar combisystems evaluated in Task 26 (Weiss, 2003)

4. Conclusions

Methods from IEA Task 26 were used in this paper to characterise a combisystem operating in Australia, based on real system performance data. This represents one of the first attempts to optimise this technology in the Australian climate and market context. As a means to develop low (or zero) carbon building, the optimisation focused on reducing the auxiliary energy used by the system. A validated TRNSYS 17 model was used to conduct this analysis and the impact of the auxiliary energy on the overall fractional thermal savings.

Results showed that by removing the need for the auxiliary energy to directly enter the tank and to boost DHW in before delivery to the load that fractional thermal savings could be increased by up to 15%. The volume maintained in the tank only needed to then meet thermal

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[3] Advanced direct solar floor , France

[4] Space heating store with double load-side heat exchanger for DHW, Switzerland

[5] Two stratifiers in a space heating storage tank with an external load-side heat exchanger for DHW, Germany

comforts of the hydronic space heating, due to the tailoring of the system to Australia this could be lowered to 45˚C.

A key limitation of this study is that optimisation did not consider designs with a higher system capital cost compared to the reference case. Increasing the number of storage tanks and auxiliary boosters may achieve further thermal savings and should be considered in future studies. Start-up losses, pipe losses and stagnation effects were not considered in this study and must be taken into account when designing a system for a winter load as it will be oversized in summer. The impact of stagnation effect on performance and lifetime of the system is unknown. The most promising areas to bring these two limitations together is in seasonal thermal storage and should be pursued to harness the Australian summer irradiation.

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